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Estimating social-ecological resilience: fire management futures in the Sonoran Desert

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Abstract. Resilience quantifies the ability of a system to remain in or return to its current state following disturbance. Due to inconsistent terminology and usage of resilience frameworks, quantitative resilience studies are challenging, and resilience is often treated as an abstract concept rather than a measurable system characteristic. We used a novel, spatially explicit stakeholder engagement process to quantify social-ecological resilience to fire, in light of modeled social-ecological fire risk, across the non-fire-adapted Sonoran Desert Ecosystem in Arizona, USA. Depending on its severity and the characteristics of the ecosystem, fire as a disturbance has the potential to drive ecological state change. As a result, fire regime change is of increasing concern as global change and management legacies alter the distribution and flammability of fuels. Because management and use decisions impact resources and ecological processes, social and ecological factors must be evaluated together to predict resilience to fire. We found highest fire risk in the central and eastern portions of the study area, where flammable fuels occur with greater density and frequency and managers reported fewer management resources than in other locations. We found lowest fire resilience in the southeastern portion of the study area, where combined ecological and social factors, including abundant fuels, few management resources, and little evidence of past institutional adaptability, indicated that sites were least likely to retain their current characteristics and permit achievement of current management objectives. Analyzing ecological and social characteristics together permits regional managers to predict the effects of changing fire regimes across large, multi-jurisdictional landscapes and to consider where to direct resources. This study brought social and ecological factors together into a common spatial framework to produce vulnerability maps; our methods may inform researchers and managers in other systems facing novel disturbance and spatially variable resilience.

Key words: adaptation; coupled natural-human systems; fire regime; management activities; management objectives; social-ecological systems; Sonoran Desert; stakeholder engagement.

Introduction

Resilience is defined as the quantity of perturbation a system can absorb without permanently transitioning to a novel stable state (Gunderson 2000). Under conditions of increasing global change, resilience to new, intensified, or interacting disturbances will shape biodiversity and ecosystem services. Promoting resilience is a mandate of many public land management agencies in the United States (Aslan et al. 2018). In conservation and resources management, resilience is often viewed through a purely ecological lens. However, ecological resilience is fundamentally influenced by and influences the social realm. Social systems may affect ecological resilience by dictating management values and hence activities and priorities, defining desired ecological state characteristics, imposing stressors and disturbance events, and enabling or preventing management interventions of certain types and at certain scales (Adger 2000, Aslan et al. 2018). Social systems also exhibit their own resilience, retaining or losing characteristics in the face of disturbance.

Resilience is often discussed in an abstract manner, due to inconsistent terminology across disciplines and the difficulty of defining a system's state (Standish et al. 2014, Hosseini et al. 2016, Quinlan et al. 2016). Yet quantifying resilience across landscapes is essential for effective planning and management in the face of changing conditions (Angeler and Allen 2016). Ecological factors that influence resilience in many systems include temperature and precipitation variability, biodiversity, environmental and geomorphological heterogeneity, and

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traits of native species and communities (Groves et al. 2012, Keppel et al. 2012, Dickson et al. 2014, Quinlan et al. 2016). Social factors include flexibility of management tools and responses, availability of resources, constraints such as regulations and social pressures, and ongoing disturbances such as fire ignitions, road construction, recreation, etc. (Quinlan et al. 2016, Aslan et al. 2018). Whether the social-ecological system at a given site is resilient to disturbance will fundamentally depend on both the starting-point ecological conditions and the social conditions at that location. For example, social-ecological systems with high habitat connectivity, genetic diversity, topographic heterogeneity, flexibility of management choices, and abundant management resources will demonstrate higher resilience than systems lacking these factors. If a site is high in ecological resilience factors but not social resilience factors, it may return to its former state after disturbance without social intervention. However, if a site is low in ecological resilience factors but high in social resilience factors, social interventions such as active restoration efforts might help the system revert to its previous state following perturbation.

In spite of the inherent interdisciplinarity of resilience, studies measuring and predicting resilience at a landscape scale rarely incorporate both social and ecological factors (Folke 2006, Reyers et al. 2013). Methods of data collection, quantification, and scales vary between social and ecological science, making it difficult to match data from the two realms and thus arrive at a truly interdisciplinary assessment of resilience (Zurlini et al. 2018, Schlueter et al. 2019). In light of these challenges, we set out to trial a novel approach to quantitatively estimate social-ecological resilience by matching spatial scales. We aimed to develop across our focal region a truly interdisciplinary estimate of resilience that would enable us to evaluate geographic variation across the region, as well as to quantitatively examine the relative influence of specific social and ecological factors in resilience estimates.

Thus, with this work we hoped to present a spatially explicit, interdisciplinary estimate of landscape-scale resilience that could serve as a case study to guide and inform similar efforts elsewhere. To do so, we used a GIS to map both ecological and social factors together, thereby bringing them into a common lens and spatial scale. We focused on ecosystem management as a key area of intersection between social and ecological realms, constrained both by social factors such as resources, mandates, and information and by ecological factors such as species assemblage, disturbance, and climate. As changing fire regimes are among the most pervasive drivers of rapid environmental change worldwide (Nolan et al. 2018), we selected as our focal study system a non-fire-adapted ecosystem currently facing fire regime change: the Sonoran Desert of Arizona, USA. We defined the current state of the social-ecological system as the set of ecological characteristics and management objectives in place at any given location across the study area. We defined social-ecological resilience as the ability of the system to remain or return to that state in a context of disturbance (fire regime change). Although we cannot know with certainty which portions of the study area are resilient to fire disturbance without waiting years or decades after each disturbance event and chronicling recovery, we aimed here to estimate and predict resilience by quantifying ecological and social aspects of resilience and modeling them across the study area in a spatially explicit manner. Via our data collection and analysis, we determined where across the study area existing management objectives are likely to continue to be reached, using current or alternative management activities. Our work exemplifies the opportunities and challenges of integrating social and ecological indicators of resilience into a coupled-systems, quantitative framework.

Methods

In this study, we used existing ecological layers and a stakeholder mapping approach to develop quantitative maps of social-ecological resilience to fire across the EPA Level III Sonoran Desert Ecoregion of Arizona. We used an overlay analysis to map coupled social-ecological resilience across the region. This analysis enabled us to identify areas of likely low and high resilience. Since resilience is meaningless unless examined in light of disturbance risk, we also modeled across the landscape both ecological and social aspects of fire risk. We then plotted resilience against modeled ecological and social fire risk to assess vulnerability across the study region.

Study system

The Sonoran Desert is the most biologically diverse desert in the United States and also one of the regions of fastest human population growth, with more than 6 million residents according to the 2010 U.S. Census (Dimmitt et al. 2015). Due to lack of fuels continuity in native plant communities, the Sonoran Desert is considered non-fire-adapted; occurrence of fire reduces both plant and associated animal diversity at local scales (McCaffrey 2015). However, fire risk has been increasing across the region in recent decades (Gray et al. 2014). Emergence of a novel, high-frequency fire regime in the Sonoran Desert is driven by increasingly variable precipitation in combination with the spread of invasive, fine fuels (Seager et al. 2007, Abatzoglou and Kolden 2011, McDonald and McPherson 2013, Moloney et al. 2019). These changes impact native plant communities with limited inherent resilience to disturbance, placing desert systems at risk of fundamental ecosystem state change (Abella 2009, Brooks and Chambers 2011). That is, a feedback loop promoting fire-adapted nonnative species threatens to turn burned Sonoran Desert ecological communities into grasslands dominated by nonnatives (McDonald and McPherson 2013). Resource managers and restoration professionals in the Sonoran confront biological invasions and aim to reduce fire risk in order to effectively retain functioning ecosystems and native Sonoran Desert biodiversity on the landscape (McCarty 2001). In the United States, the Sonoran Desert Ecoregion consists largely of government-managed land, but is a patchwork of federal, state, and local jurisdictions, military bases, and tribal reservations. Management responses to fire across the region are varied and span a range of jurisdictional mandates as well as constraints and resources (Aslan et al. 2021).

Modeling ecological aspects of resilience

We gathered ecological spatial layers to (1) predict ecological large fire risk over the next 20 and 40 yr across the study area, so that we could present risk maps to managers and discuss their responses, and (2) include ecological components of system resilience in our coupled systems GIS. We defined fire risk throughout the study as the probability of large fire (>1,000 acres [1 acre = 0.40 ha]) if an ignition were to occur, and used the current and prior year maximum NDVI as predictors of annual fire risk (after Gray et al. 2014). We also included as dynamic model variables climate variables (total winter precipitation, winter mean daily minimum temperature, and fire season mean daily wind speed, maximum temperature, and humidity) to predict past and future fire risk (after Gray et al. 2014). Fixed variables in the model included road density, distance to urban development, surface heat load index, topographic roughness, elevation, aspect, and slope (Gray et al. 2014). To forecast fire risk into two future time periods, it was first necessary to forecast the dynamic predictor variables. We used data at 4-km resolution, downscaled from 12 Global Climate Models (GCMs), to forecast the meteorological predictors. To forecast NDVI into the future, we used 32 yr of historical precipitation and NDVI data to statistically relate cool season precipitation to the subsequent maximum annual NDVI. Predicted NDVI values were plotted against observed NDVI values and averaged over the whole study area. With the results of that statistical relationship and using available forecasted precipitation data, we were able to forecast annual maximum NDVI into the future.

To build models of fire risk, we used points that either burned historically in a large fire or points that burned but did not become a large fire and related these to the predictor variables. We included the entire U.S. Sonoran Desert ecoregion, so that we had many historical fires to draw from, and from these burned/unburned points created 10 of these independent, random data sets, which were combined with the accompanying predictor variables described above to build 10 independent models that predict the probability of a large fire. The annualized estimate of fire risk was then averaged over these 10 data sets and over 12 GCMs. This approach thus incorporated the variability resulting from independent fire risk models as well as variability resulting from future climate projections, which heightened the robustness of final estimates. This effort focused on the maximum fire risk (i.e., an extreme rather than the mean) in each of three time periods. This decision was based on the concern that even a single, extreme climate and fire year over a 20-yr period can cause changes in land cover (Gray et al. 2014), and this worst-case scenario can help focus adaptation planning. While some areas may not show significant change in maximum risk from the past to the future, even a slight increase would indicate a meaningful and challenging change over the conditions a given manager has experienced in their tenure.

To model ecological aspects of resilience, we mapped variables indicative of a system's likelihood of retaining its characteristics and species in the face of disturbance, as indicated in ecological resilience literature. We thus created layers for topographic diversity, geophysical diversity, vegetation diversity, water availability, habitat connectivity (sensu Theobald et al. 2012), species richness, and human modification (Table 1). To create ecological rasters that could later be combined with social rasters, we summed these indicators to obtain a single value per location for ecological aspects of resilience across the Sonoran Desert.

Modeling social aspects of resilience

To collect data on social aspects of resilience, we designed a mapping exercise for land managers, who were the stakeholders for this study. We reached out to managers of all governmental jurisdictions in the study area (county, state, federal, and tribal) and invited them to participate in the study. To identify invitees, we examined land ownership maps of the region and used internet searches and our existing contacts to match management units to individual managers. In all, we obtained participation from managers of 25 jurisdictions, accounting for 79% of the study area (Table 2). We included only governmental jurisdictions, since private landowners represent an extremely small proportion of the study area (<8%). Throughout the below, we use the term "jurisdiction" to refer to a contiguous land area managed by a given government agency.

To all participating land managers, we presented background information about fire in the Sonoran Desert, drivers and consequences of fire regime change, and social-ecological resilience. We provided managers with maps of their jurisdictions displaying the projected large fire risk we had developed; maps included 10 randomly generated points established within the jurisdiction of each manager. We asked managers to identify on the map the locations of their various management objectives and activities, as well as the likelihood that these objectives and activities would be effective under projected future fire risk (Appendix S1). Managers

Table 1. Indicators used to compile an ecological resilience map of the Sonoran Desert.

Indicator	Metric	Scale
Topographic diversity	Standard deviation of slope from DEM (minimum = 0, maximum = 1) using moving window (focal statistics) from 30-m base map to 270-m windows.	high standard deviation = 0, low standard deviation = 1
Geophysical diversity	Shannon-Weaver Equitability Index (SWEI) at multiple spatial scales, equivalent to average sizes (1.2–115.8 km radii) of HUC 4–16 watersheds. Indices derived at multiple scales were then combined to produce a single multi-scale index at 30-m resolution	high SWEI = 0, low SWEI = 1
Vegetation diversity	Count of unique threatened, endangered. and sensitive (TES) classes.	low SWEI = 0, high SWEI = 1
Habitat connectivity, HC	Sensu Theobald et al. (2012); resistance values for least-cost calculations based on the inverse of a landscape “naturalness” value.	high HC = 0, low HC = 1
Species richness, SR	Mean of rarity-weighted species richness.	high SR = 0, low SR = 1,
Human modification, HM	Sensu Theobald (2013); a metric that incorporates development, agriculture. energy production and mining, transportation and service corridors, biological resource use, human disturbance, natural system modification, invasive species, and pollution.	low HM = 0, high HM = 1
Water availability	Path distance from surface water features (springs, seeps, perennial rivers, perennial lakes, and ponds from the National Hydrography Dataset (1:24,000; U.S. Geological Survey 2019), with the path surface defined by the DEM layer.	low distance = 0, high distance = 1

Notes: Each indicator is paired with a description of how the metric was calculated and the scale used. Indicators were scaled from 0–1, with 0 being the lowest concern for managers and 1 being the highest concern for managers.

Table 2. Jurisdictions, with managing agencies, from which a manager participated in this study.

Jurisdiction	Agency	No. unique jurisdictions
Military	Department of Defense	3
Non-military Federal	Bureau of Land Management	3
Non-military Federal	Bureau of Reclamation	1
Non-military Federal	National Park Service	4
Non-military Federal	US Fish & Wildlife Service	3
Non-military Federal	US Forest Service	2
State	State of Arizona	2
County	County (Various)	4
Tribal	Tribal (Various)	3

provided this information for all of the random points and also for polygons they hand-drew on printed maps to indicate areas of particular concern (e.g., locations of cultural resources or endangered species management) in light of fire regime change. Following interviews, we transferred all management activity and objective information into a GIS. To do this, we transcribed into the digital platform the polygons of areas identified by participants as important. We attributed both random points and polygons with the objectives and activities relevant to those locations, as well as the manager-reported likelihood that activities could continue to achieve objectives, new activities could be employed, or new objectives could be adopted (Appendix S1). For analysis, we classified participant-reported management objectives and current management activities in the GIS into nine objective categories and 12 activity categories (Table 3). We then imported rasters of each category, along with levels of likelihood as described above, as a grid of points into R version 2.14.1 (R Core Team 2012).

After completing the mapping exercise, participants were asked to complete a paper survey reporting their experience with past environmental change, fire, and adaptive management. Responses to survey statements were recorded on Likert scales as 1–7 (strongly disagree to strongly agree; Appendix S1). Survey questions were designed to assess jurisdictions’ past adaptability and constraints to change, and Likert-scale values were mapped onto the GIS at the scale of the jurisdiction. For institutional reasons or due to resource constraints, some agencies or individuals have difficulty changing their management methods, while others are more adaptive (Haase 2013, LeQuire 2013). Quantifying the flexibility of each jurisdiction can be critical to assessing the implications of changing conditions for management.

We defined the “state” of the social system in this study as the set of management objectives at a location, and the social element of resilience as the likelihood that current management objectives would continue to be met, either using current management practices or via the adoption of new practices. To quantify this, we used spatially explicit data from both the interviews and the surveys. From the interviews, we used the answers (very unlikely to very likely) to the questions “[Given predicted future fire regimes] How likely are you to continue to meet current management objectives?” and “[Given predicted future fire regimes] How likely are you to change current management practices in order to be able to meet current management objectives?” Participants

TABLE 3. Management objective and current management practice categories and descriptions.

Category	No. locations	Description
Management objective		
Conservation	160	habitat/species protection, ecological integrity, conservation, wilderness management, restoration, resource managed fires
Resource extraction	11	mining
Grazing	39	grazing
Agriculture	9	agriculture
General fire suppression	188	fire suppression, roadside fire reduction, lightning strike monitoring
Human/infrastructure protection	74	infrastructure protection (private and commercial plus roads, powerlines, visitor centers, and campgrounds), human safety (nearby communities), air quality, communications, water management (flood control)
Military	38	military (training, etc.) and border activities (patrol, enforcing border laws, controlling illegal border activity, border patrol cooperation)
Recreation	126	hunting, viewshed protection, infrastructure, camping, scenic driving, general
Cultural resource protection	74	sites and infrastructure, historical sites and buildings, saguaro harvest, traditional uses of area and plants
Current management practice		
Fire management	223	general suppression, fire breaks, fuel breaks, access/pre-positioning for fire crews, let burn/monitor, prescribed burns/management fires/fire regime, fuel load monitoring, road and trail closures, shooting restrictions, burning/fire restrictions/bans, restricting access to culturally important sites, increasing patrols, hazard mitigation
Preventative vegetation/invasives removal for fire	121	(category is for preventative veg/invasives removal for fire) general thinning, site-specific fuel removal (around infrastructure and roads), herbicide or manual removal invasives/grasses removal, mastication, tamarisk removal, general invasive grasses removal, buffer creation, mowing, grazing for fuel management, grazing for invasives/grasses removal
Grazing	39	leasing for grazing, permits for grazing
Outreach and education	41	education, PSAs
Native species management	87	monitoring for conservation management (invasive/exotic species including feral horses, native vegetation long-term, wildlife populations (like pronghorn and Yellow-billed Cuckoo), endangered species, birds (Eagles, etc.), rare species, riparian habitat), restoration (native species seeding, of general species/habitat, of species for cultural use), maintenance of vegetation and native plants (cultural uses, medicinal)
Crops	3	leasing, irrigation
Resources from partnerships	44	funding, partnerships/agreements, general, partnering with local fire departments
Leasing and permits	6	other (not crops or grazing) leasing and permits, “improving stipulations”/guidelines/ rules for mining
Infrastructure development	7	general irrigation (not for crops), improved fencing, improved wells/other water infrastructure, fire-wise campgrounds infrastructure and training
Soil and watershed protection	3	erosion prevention/retention for flood control or other reasons
Cultural and social resource protection	27	maintenance of recreational sites, cultural resources, cultural sites, native plants (for cultural uses, medicinal reasons), preventative maintenance
Recreation	126	hiking, camping, hunting/shooting, OHV/ORV; if “recreation” was listed as a management objective, this category was used in current management

Notes:: The descriptions listed are groups of keywords that managers used in their interview responses. Categories of manager-reported objectives and activities were associated with random points and manager-identified polygons (i.e., “locations”) included in social resilience estimation. Some locations were associated with multiple objectives and/or activities.

responded to these questions with respect to specific polygons or points using a Likert scale from 1 to 5 (where 1 = very unlikely, 5 = very likely), and those Likert values were mapped into the GIS as point and polygon attributes. From the survey, our estimate of social resilience was informed by the responses (Likert scale 1–7) to the statements “In my organization, we expect and try to prepare for ‘surprises’ in ecosystem behaviors.” and “I have seen my organization successfully change management strategies when necessary” (Appendix S1).

We defined social fire risk as a combination of four factors influencing whether an ignition becomes a large fire. From the interviews, we included whether or not a given location (as defined at the point or polygon level) reported (1) fire suppression as a management objective and (2) fire management as a current management practice. From the surveys, we included the responses to two statements about organizational resources: (3) “My organization has sufficient resources and personnel to manage fire and fuels on a day-to-day basis” and (4) “My organization has sufficient resources and personnel to manage fire and fuels during fire incidents.” The responses to each of these questions were scaled from 0 to 1 and summed for use in the overlay analysis (see *Overlay analysis: Coupled ecological and social estimate of resilience*).

Although the indicators of ecological resilience that we included were measured objectively, these indicators of social resilience are clearly subjective, reflecting the experiences and opinions of the interviewed land managers. This is an important distinction to acknowledge, but we felt that our interview approach allowed us to capture the lived experiences of the managers and therefore incorporated the subtleties of fire response options that are difficult to adequately equate to more objective indicators of social management context such as parcel size, funding, staffing, etc.

Overlay analysis: coupled ecological and social estimate of resilience

We developed spatial layers of social-ecological fire risk as well as social-ecological resilience (Appendix S1). We scaled all ecological and social measures on a 0–1 scale, with 0 indicating lowest concern for managers and 1 indicating highest concern (Dressel et al. 2018). We used a simple additive model (i.e., a linear relationship) between ecological and social factors because, since research on quantitative social-ecological resilience is so limited, we are unable to defensibly select any nonlinear relationship that would mathematically inflate the contribution of either the social or ecological factors to the overall estimate of integrated resilience. To calculate total risk across the Sonoran Desert, then, we summed the ecological and social risk layers, and rescaled them to 1, giving equal weight to each. We did the same for total resilience. When rasters were at different resolutions, we resampled them to make all rasters equivalent in resolution to the social rasters. We performed a coarse check of sensitivity to the social component within the total resilience assessment by up-weighting or down-weighting the social resilience raster and comparing the resultant, scaled total resilience values for the socially up-weighted, socially down-weighted, and equal weights rasters.

Last, we plotted total risk against total resilience to determine vulnerability of locations to fire across the Sonoran Desert (sensu Comer et al. 2012). Vulnerability can be considered the intersection of system sensitivity (which in our study we equate to risk) and resilience, with the most vulnerable areas being those where high sensitivity and low resilience intersect (Comer et al. 2012). We translated these categorical vulnerability scores into a map to identify areas of low, medium, high, and very high vulnerability within the Sonoran Desert.

Results

Social-ecological fire risk was generally higher in the southern and eastern parts of the Sonoran Desert study region. Mathematically, this was due to fewer managers that reported fire suppression objectives or fire management practices (generally southern), fewer managers that agreed that they have sufficient resources to manage fire and fuels both on a day-to-day basis and during fire incidents (generally eastern), and higher incidence of fuels (Fig. 1).

Ecological aspects of resilience to fire were generally highest in the south-central and the far northwest of the study area, and lowest in the north-central and northeast, where Sonoran Desert transitions to other, higher-elevation ecosystem types characterized by greater continuity of fuels (Fig. 2). High geophysical and vegetation diversity, as well as increased distance from human-modified landscapes, were the main positive drivers, mathematically, of estimated resilience on the ecological side. Social aspects of resilience were lowest in the southeastern study region as well as in a few scattered jurisdictions in the north, and highest in the southwest (Fig. 3). The estimate of resilience on the social side was largely driven in the model by the manager-reported likelihood that management objectives would continue to be met under predicted future fire regimes, as well as whether or not an organization had changed management strategies in the past.

Overall, combined social-ecological fire resilience was estimated as low or very low for 12.28% of the study area (Fig. 4). Social-ecological resilience was estimated as lowest in the southeastern portion of the study area, where ecological fire risk is high due to increased fuel densities, management resources are lower than in the central portions of the study area, and managers reported low likelihood that current objectives will be achievable under future increased fire risk (Fig. 4). Where total risk was medium to high and total resilience was low, locations exhibit high vulnerability (Fig. 5). Areas of medium vulnerability and areas of high vulnerability each amounted to 46%, respectively, of the total study area (Fig. 5). The majority of very high vulnerability areas fell within the eastern portions of the study area and amounted to 7% of the total study area (Fig. 5).

Some areas that had low social-ecological fire risk in the central and northern portions of the study area also have high predicted social-ecological resilience in our analysis, due mathematically to low incidence of fuels or high management resource availability. Areas of lowest total risk were in the western part of the study area, largely due to low projected incidence of fuels (Fig. 1). These areas corresponded to some of the areas of the highest estimated total resilience. Some areas of the southwestern Sonoran had high total risk, since managers reported little fire preparedness in the event of a rare high precipitation period leading to a short-term biomass burst, but also high estimated total resilience

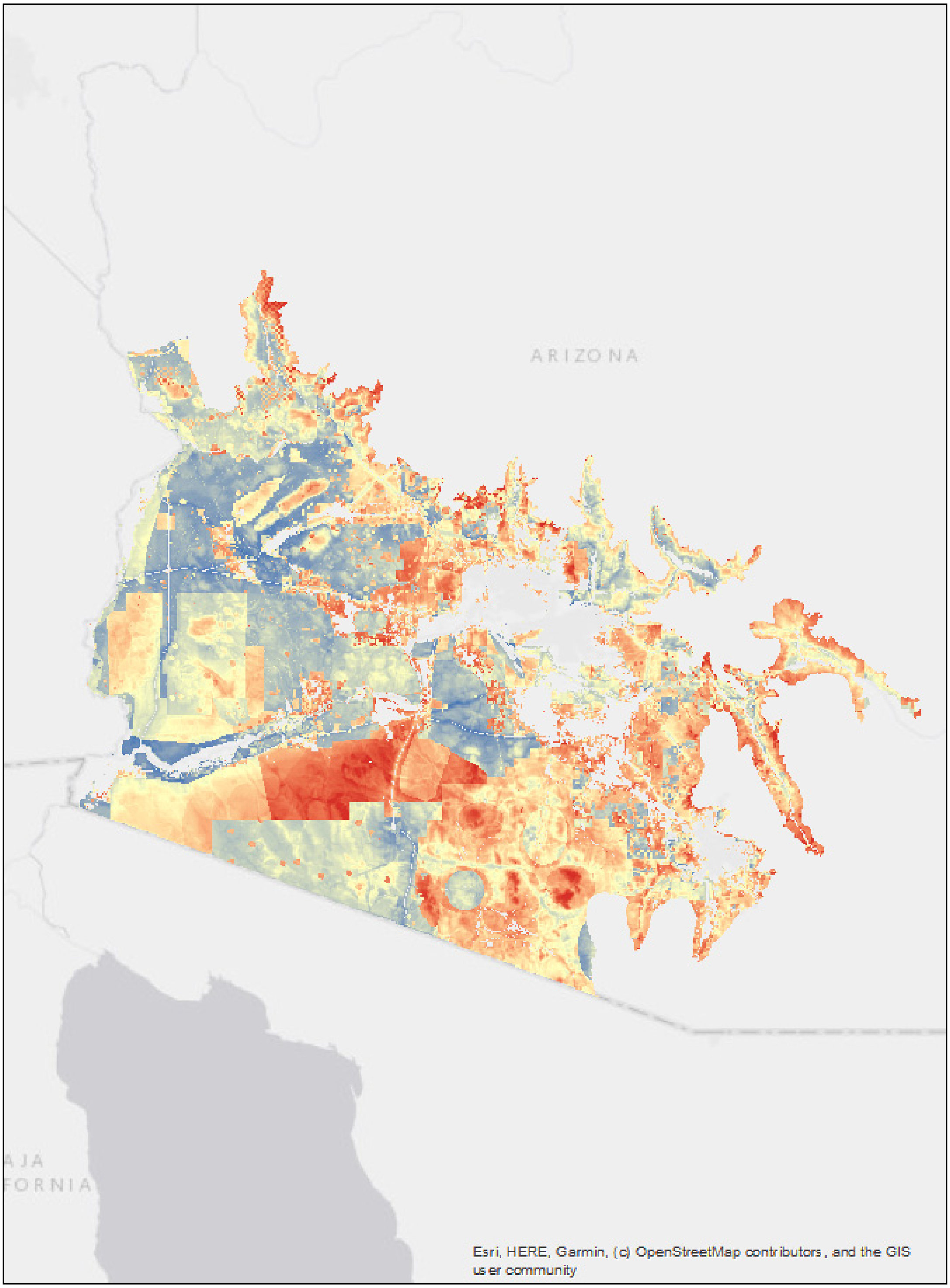

FIG. 1. Socioecological fire risk in the Sonoran Desert Ecoregion in Arizona, USA. Warmer colors indicate higher risk and cooler colors indicate lower risk.

because managers were confident that their overall objectives could continue to be met. Across the full study area, very few locations fell into the low vulnerability category (low risk and high estimated resilience; 1% of the total study area), and those were all in the western portion of our study area (Fig. 5).

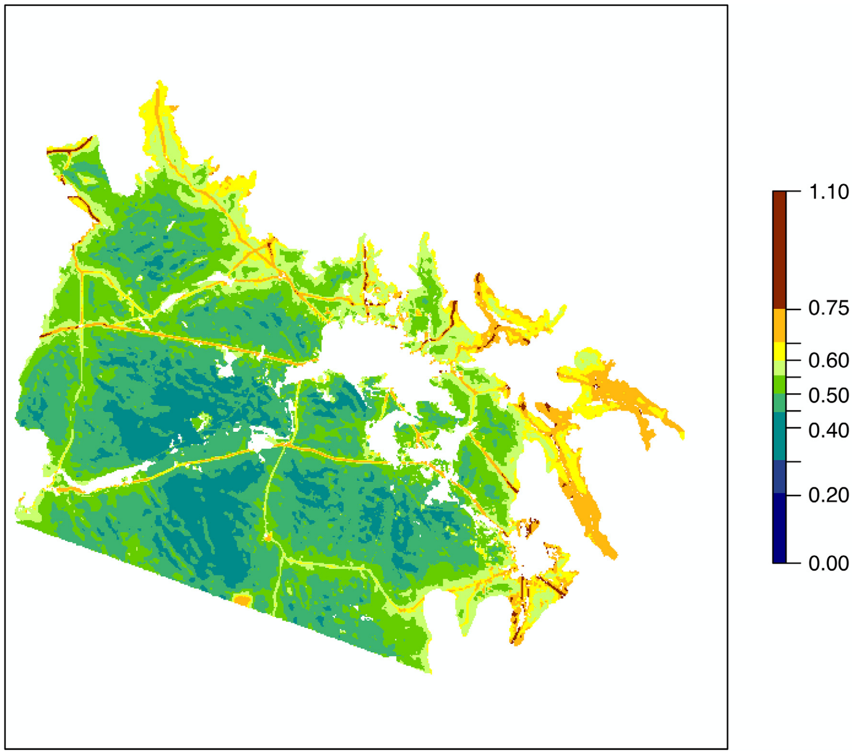

FIG. 2. Ecological aspects of resilience to fire in the Sonoran Desert Ecoregion in Arizona, USA. Warmer colors indicate lower resilience and cooler colors indicate higher resilience. Ecological resilience is a composite index from 0 to 1, with 0 being highest ecological resilience and 1 being lowest. The index is composed of measures of topographic diversity, geophysical diversity, vegetation diversity, habitat connectivity, species richness, human modification, water availability (Table 1). All measures are equally weighted.

Down-weighting social aspects of resilience in relation to ecological aspects of resilience resulted in lower estimates of overall resilience compared with equal weighting. Likewise, up-weighting of social aspects of resilience in reference to ecological aspects resulted in higher resilience scores overall, with higher land area, particularly in the southwest portion of the state, classified as low vulnerability. This indicates that despite the severity of the current and predicted future fire regime, managers remain confident in the ability of their organization to respond and adapt to disturbances to the ecological landscape that these fires bring.

DISCUSSION

Our approach generated estimates of social-ecological fire resilience as an overlay of indicators of social resilience (that is, whether a system will continue to be managed for current objectives in the face of disturbance) and indicators of ecological resilience (imposed as spatially explicit biophysical layers predictive of whether a system will return to its current ecological state following fire). The social-ecological state of the system in our models is thus the combination of ecological characteristics and the management objectives and activities occurring at a given location on the landscape. Our analysis found that areas in the eastern and southern portions of our study area generally had the highest social-ecological fire risk. These areas also tended to display lower estimated social-ecological fire resilience. Together, these findings indicated high or very high vulnerability in the eastern and southern Sonoran Desert of Arizona. On the ecological side of our models, this vulnerability is driven by relatively high vegetation cover/fuels, low elevation, low geophysical and vegetation diversity, and proximity to human-modified landscapes, particularly roads (key sources of ignition). Vulnerability on the social side of the models is driven by a lack of active fire suppression (either due to limited resources or policy), a perception by managers that management objectives cannot continue to be met under projected future conditions, and relatively lower ability among jurisdictions to change management strategies to meet current objectives.

Although some areas of the southwestern Sonoran Desert had equal or higher fire risk than the eastern Sonoran Desert, these areas also had some of the highest predicted resilience. The high risk in these areas, mathematically, is driven more by social than ecological factors, reflecting a lack of management options and

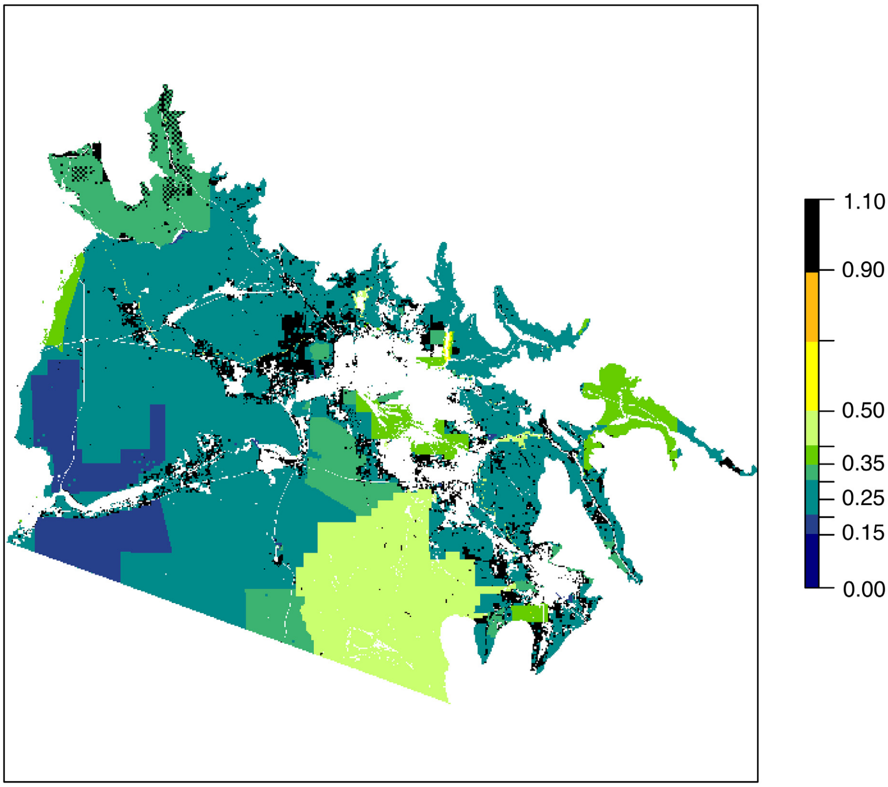

FIG. 3. Social aspects of resilience to fire in the Sonoran Desert Ecoregion in Arizona, USA. Warmer colors indicate lower resilience and cooler colors indicate higher resilience. Social resilience is a composite index from 0 to 1, with 0 being highest social resilience and 1 being lowest. The index is composed of Likert responses of interviewees respondents to questions about likelihood to meet current management objectives and change current management practices to meet current management objectives, given predicted future fire regimes and of survey respondents to questions about organizational preparedness for surprises and ability to change (see Methods). All measures are equally weighted.

planning with regard to fire. The higher estimated resilience of these southwestern areas reflects relatively lower predicted fuels and high confidence on the part of managers that objectives will continue to be met into the future. These high estimated resilience levels indicate that if risk can be reduced somewhat, by for example setting suppression and management objectives even for rare fires, these areas would be less vulnerable. Indeed, some areas of the western and northwestern Sonoran Desert had low fire risk, as well as high resilience. These areas had low vulnerability, driven in the models by low NDVI, high plant diversity, active fire suppression and management planning, organizational flexibility, and sufficient management resources.

Implications of coupled systems resilience

Previous attempts to measure purely ecological resilience in other systems have often centered on sources of species' recolonization after disturbance, diversity of functions, and refugia (Timpane-Padgham et al. 2017, Looy et al. 2019) Attempts to measure purely social resilience have involved assessments of community cohesion, resource availability, communication, and other indicators of the speed and trajectory of recovery from disturbance (Abramson et al. 2015, Aldrich and Meyer 2015). However, landscapes are both social and ecological, and assessing social-ecological resilience as a combined metric is difficult but necessary to adequately predict recovery (Sterk et al. 2017).

Most resilience thinking in ecosystem management remains at a conceptual level, as a framework for understanding and predicting qualitative changes and the dimensions along which interventions may occur (Folke et al. 2016, Millar et al. 2016). Previous efforts to quantitatively predict and map ecosystem resilience to fire under novel fire regimes have included a number of studies that have predicted vulnerability using remote sensing of vegetation characteristics (reviewed in Smith et al. 2014). Continued improvement in on-the-ground understanding of the vulnerability implications of specific vegetation characteristics is needed in order to increase the confidence of such projections (Smith et al. 2014). Aspects of resilience, vulnerability, and state change have been quantified to model ecological resilience (Allen et al. 2016), for example in modeling of vegetation

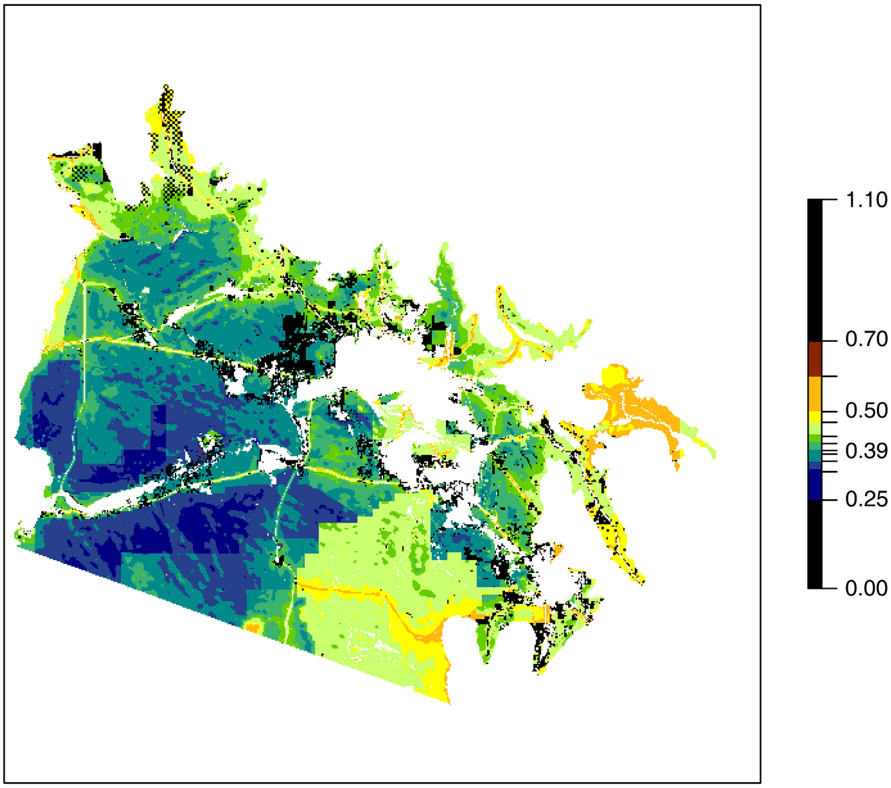

FIG. 4. Socioecological resilience to fire in the Sonoran Desert Ecoregion in Arizona, USA. Warmer colors indicate lower resilience and cooler colors indicate higher resilience. Total resilience is a composite index of both ecological and social resilience that ranges from 0 to 1, with 0 being highest total resilience and 1 being lowest.

spatial configuring and fire response (Gowda et al. 2019) as well as in projections of climate exposure for southwestern forests under different emissions scenarios (Thorne et al. 2018). These efforts have been based entirely on biophysical modeling inputs. Cumming et al. (2005) identified empirical components of system identity in a case study approach to measuring resilience, listing both social and ecological components of that identity and how change in each would signify a state change. The approach was not translated to a coupled quantitative assessment; rather, each element was separately identified as important to track in order to estimate resilience (Cumming et al. 2005). Quantitative assessment of resilience that includes measurements of both ecological and social resilience elements remains relatively little explored in the global change literature, even though social systems dictate resources management techniques and their effectiveness (Bottom et al. 2009). Modeling of the probability of ecosystem type change given specific management activities has been used to assess system resilience under each management scenario (Peterson 2002, Ungaro et al. 2017, Zurlini et al. 2018); in these cases, however, the application has been one-directional, assessing the effects of different social systems on ecological systems but not vice versa. By defining our focal system's state in both ecological and social (management) terms and quantifying the likelihood of truly coupled social-ecological state change in a common spatial framework, our work applies a novel integrated systems analytical technique that may be useful in other systems as well. That said, limitations of our approach include the subjectivity of the manager responses, on which we based our estimates of social indicators of resilience, as well as the modeling assumptions inherent in our calculations, such as the additive nature of the social and ecological resilience models. Our approach is a step forward in aligning social and ecological resilience estimates, but we encourage managers to use outputs with caution and to carefully monitor system recovery following fire events, to determine whether recovery trajectories bear out the resilience predictions presented here.

The fire history in our study area exemplifies the importance of social-ecological resilience to fire regime change. In the Southwest, average temperatures are on the rise but observed and predicted precipitation displays more variability (Jardine et al. 2013). Specifically, rainfall is becoming patchier, both spatially and temporally: on any given year, most sites receive less rain than the historical average, but in rare years rainfall far

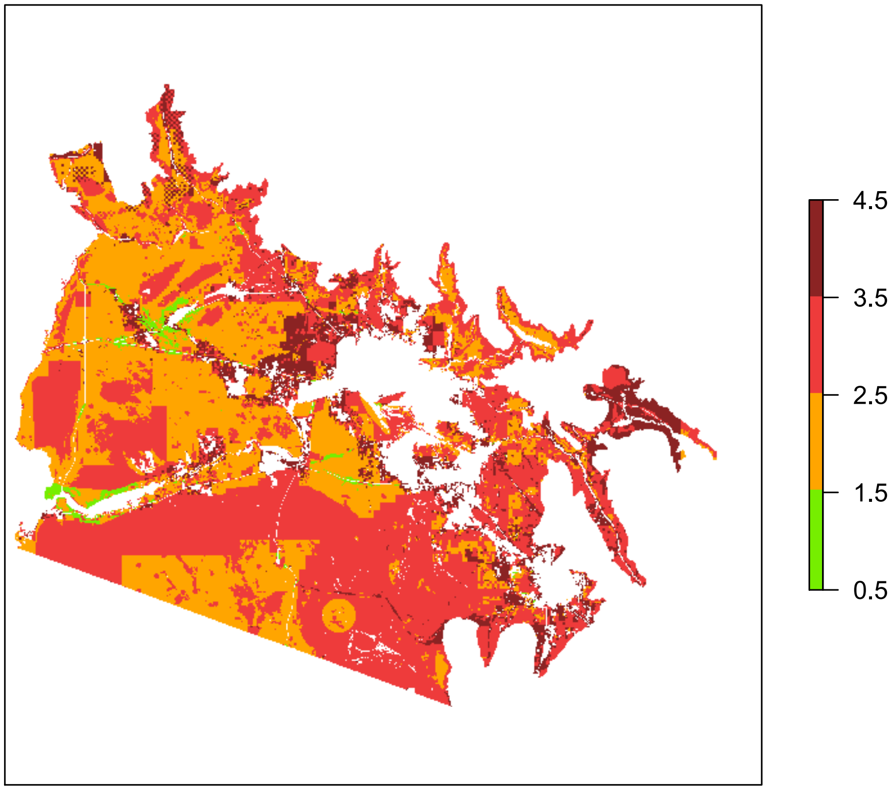

FIG. 5. Vulnerability in the Sonoran Desert, representing the relationship between risk and resilience. Colors on the graph and map correspond to low (green), moderate (yellow), high (red), and very high (maroon) vulnerability. Vulnerability definitions and plotting sensu Comer et al. (2012), with risk equated to sensitivity. Vulnerability is an index of the intersection of risk and resilience on a scale from 0 to 5, with 5 being highest vulnerability and 0 being lowest.

exceeds that average (Coe et al. 2012). As an example of the rare precipitation burst and its relevance to fire, in the winter of 2004–2005, southeastern Arizona received an unusually high amount of precipitation, and as a result the lower Sonoran Desert accumulated a much greater load of standing nonnative and native annual grass biomass than normal (Gray et al. 2014). After the winter rains, high temperatures during an unusually hot and lengthy pre-monsoon summer dried out this biomass, which had formed a continuous layer connecting native vegetation patches. This process fueled an unprecedented number of fire ignitions and acres burned in the arid spring and summer of 2005. Across the Lower Sonoran Desert Ecoregion, the fires of 2005 accounted for 89% of the total area burned between 1989 and 2010 (Gray et al. 2014). In interviews conducted for this study, managers of burned sites reported very poor recovery after this disturbance, with some locations remaining barren nearly 14 yr after the fires.

Although the winter of 2004–2005 was exceptional, such unusual episodes are likely to arise in the Sonoran with greater frequency as occasional wet winters are followed by ever-lengthening hot, dry, pre-monsoon summers (Jardine et al. 2013, Gray et al. 2014). In fact, the pattern recurred in the winter of 2018–2019, after our interviews were completed, and in early summer 2019 the region experienced the Woodbury Fire, at the time considered the fifth largest fire in state history (Burned Area Emergency Response Team, *personal communication*). Furthermore, this fire took place in the eastern portion of the study area, within an area estimated by our models to be high risk/low resilience and thus high vulnerability. In our model, the region was identified as highly vulnerable due primarily to its relatively high predicted fuel loads as well as manager-reported low likelihood that management objectives may continue to be reached into the future, given projected changes in fire risk. Even if wet winters arise only once every 20 yr, the emergence of this novel fire regime may result in significant damage across the sensitive Sonoran Desert region.

The maps and assessments produced here may serve managers across the region by pinpointing locations of vulnerability to state change resulting from fire. Separately considering the effects of management flexibility and resources vs. underlying ecological conditions may help managers and collaboratives identify useful areas of intervention to support protection of native species and ecosystem services. Preparing for change in advance of perturbations can enable management entities to select and screen alternative management approaches before the need for them arises. Our work thus serves as an example of a quantitative, spatially explicit evaluation process that may be employed in other systems facing social-ecological state change, particularly when spatial planning is desirable. Furthermore, our maps of resilience identify locations that are likely to be able to return to their current social-ecological state, even following fire. Such areas may require less investment in active, expensive, post-fire restoration, for example, since current management and ecological characteristics are likely to assist in recovery. By contrast, areas of low resilience might be high priority sites for restoration investment or even altered management objectives, since recovery is otherwise unlikely.

Resilience at its heart is about state change (or lack thereof) and recovery, but relevant components of states are matters of perception. That is, a state change will only be identified as such if characteristics viewed as valuable or intrinsic to a system are lost. Understanding whether changes warrant alarm or management response entails determining what desirable states and components of systems can be and whether those desirable states are threatened by environmental change. Success in resilience management is likewise a feature of perception; what one manager sees as successful is not necessarily the same as what another manager sees as successful (Aslan et al. 2018). We aimed to understand those perceptions through our work with managers in this project by allowing their self-reported objectives to define state, such that meeting those objectives via any activity indicated that a state change had not occurred. This approach, however, required us to define social-ecological resilience and system states in this very precise and system-specific way for our work here. Integration of social and ecological definitions and elements of resilience is always challenging in its semantics and conceptual discontinuities (Timpane-Padgham et al. 2017, Aslan et al. 2018, Petersen et al. 2018), and those challenges must be taken into account when applying lessons learned from our work to other systems. Definition of state may be quite different in other studies. However, we suggest that when resource management is the focus of resilience research, a common area of intersection between ecological and social systems in conservation planning and study, management objectives may in many systems serve as an appropriate framework for state definition, as here.

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Supporting Information

Additional supporting information may be found online at: http://onlinelibrary.wiley.com/doi/10.1002/eap.2303/full

Data Availability

Data are available from the Dryad Digital Repository (Aslan et al. 2020): https://doi.org/10.5061/dryad.tqjq2bvxf